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Geometry and paleo-ice content of rock glaciers in the southeastern Alps (NE Italy – NW Slovenia)

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ABSTRACT
Rock glaciers in the southeastern Alps of Slovenia and Italy have been mapped in detail using high resolution digital elevation model and orthophotos, supported by field-based observations. A total of 52 rock glaciers with an area of 3.40 km^2 have been delineated on a rock glacier map, divided in 18 sections at a scale of 1:15,000. Several geometrical parameters of rock glaciers have been calculated and their activity degree has been inferred. 90% of rock glaciers have been classified as relict, while the rest are assumed to be of uncertain activity and might still contain some ice. The volumetric ice content and water volume equivalent of the studied rock glaciers for the period of their activity has been calculated to 0.055 ± 0.011 km^3 and 0.049 ± 0.010 km^3, respectively, which is very close to the ice volume of glaciers reconstructed for this area during the little ice age to 0.069 km^3.

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KEYWORDS
Rock glacier; volume/area scaling; water content; periglacial landforms

1. Introduction

Masses of coarse and angular debris formed as a result of downslope creep of perennially frozen ice-rich debris with peculiar transversal furrows and ridges on the upper surface, which characterize the periglacial mountain domain of several alpine areas of the world, are commonly named rock glaciers (Barsch, 1996; Haeberli, 1985; Haeberli et al., 2006). Together with glaciers they globally represent the largest cryospheric landforms of the mountain domain and widespread components of cold climate environment. They retain the majority of the available fresh water in its solid phase (e.g. Chevallier, Pouyaud, Suarez, & Condom, 2011; Nicholson et al., 2009; Rangecroft, Harrison, & Anderson, 2015). If glaciers are considered excellent climate indicators and their evolution recognized as one of the best indicators of climate change (e.g. Haeberli, Hoelzle, Paul, & Zemp, 2007), rock glaciers are generally more resilient to changes in the climate due to their debris cover (Jones, Harrison, Anderson, & Betts, 2018). One of their peculiar characteristics is to retain much of their morphology long after they have ceased moving and permafrost has thawed, displaying smoothed surface topography and gentler front slopes (Hughes, Gibbard, & Woodward, 2003).

Ice glacier content and volume are generally easy to estimate (e.g. Bolch, Menounos, & Wheate, 2010; Bradley, Vuille, Diaz, & Vergara, 2006; Chevallier et al., 2011) and it has been done in several occasions in the southeastern Alps (e.g. Colucci et al., 2015; Colucci et al., 2019; Del Gobbo, Colucci, Forte, Triglav, & Zorn, 2016; Forte, Dossi, Fontana, & Colucci, 2014), but this is not the case of rock glaciers due to their variable distribution of ice and challenging determination of the genesis (e.g. Rangecroft et al., 2015). Estimates for volumetric ice content within rock glaciers usually range between 40% and 60% according to Barsch (1996), Haeberli et al. (1998) and Hausmann, Krainer, Brückl, and Mostler (2007), although estimates of up to 70% have also been detected (e.g. Arenson, 2002; Barsch, Fierz, & Haeberli, 1979). Still considerable uncertainties remain regarding the ice content and subsequent water equivalent of the so-called inactive rock glacier (*sensu* Barsch, 1996), namely those rock glaciers which do contain ice, but are no longer mobile either due to melting of most of the upper ice layers within the terminus slope (climatically inactive), or because of topographic obstacles (dynamically inactive).

In several mountainous regions of the world and particularly in the European Alps the distribution of rock glaciers has been investigated in detail (e.g. Colucci, Boccali, Žebre, & Guglielmin, 2016b; Guglielmin & Smiraglia, 1997; Kellerer-Pirklbauer, Lieb, & Kleinferchner, 2012; Rangecroft et al., 2014; Seppi, Carton, & Baroni, 2010), but very scarce information regarding the volume estimation of ice and water equivalent at present exists, particularly if related to the distribution of relict rock glaciers, i.e. the rock glaciers that were active in the past. On the other hand,

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relict rock glaciers are recognized to have high storage capacity able to influence the water resources management in alpine catchments and mitigate the risk of natural hazards related to heavy precipitation events (Winkler et al., 2016). Nevertheless, the lack of such studies performed on carbonate rocks with high permeability such as limestones means that any further considerations on rock glaciers storage capacity would result to be over speculative in this study area.

In the southeastern Alps, the exact timing and extent of Lateglacial glaciations are still largely unknown (Kozamernik, Colucci, Stepišnik, Forte, & Žebre, 2018). On the other hand the onset and decay of rock glaciers have been related to the Younger Dryas (YD) cold phase event and the subsequent climate amelioration of the early Holocene (Colucci et al., 2016b). However, this description lacks the real size in terms of ice volume and water content which are instead known for glaciers at the LIA peak (Colucci & Žebre, 2016) but still unknown for the Lateglacial phases.

Therefore, the main purposes of this paper are: (1) to estimate the volume and calculate the available water content of each relict rock glacier in the southeastern Alps of Italy and Slovenia for the period in which they were still active and (2) to present a rock glacier map of the southeastern Alps, including the main geomorphological features (e.g. perimeter, rock glacier front) on the basis of a 1 m cell digital terrain model (DTM).

The recent production of extremely detailed topography of Slovenia and Friuli Venezia Giulia (the northeastern-most Administrative Region of Italy) areas using light detection and ranging (LiDAR) data, was a further motivation to improve the accuracy of this inventory.

Moreover, the same areas of both countries have been recently surveyed by several authors and with different purposes, in order to map and rise knowledge about the coastal areas (Biolchi, Furlani, Covelli, Busetti, & Cucchi, 2016), the Classical Karst region (Jurkovšek et al., 2016), the hydrogeological functioning of the alluvial plain (Treu et al., 2017) as well as the sinkhole occurrence and analysis (Calligaris, Devoto, & Zini, 2017). Glacial features and morphologies were already mapped by Colucci and Žebre (2016) and Žebre and Stepišnik (2016), therefore this work is part of an extensive effort aiming for a better understanding of environments and landscapes of this transboundary European area.

2. Study Area

The study area extends from 46°15′ N to 46°38′ N and from 12°25′ E to 14°37′ E, including the northern part of Friuli Venezia Giulia Region in Italy and the northwestern part of Slovenia. The study area comprehends about 6000 km^2, covering from west to east the Carnic Prealps and Alps, the Julian Alps and the Karavanke Mountains. Mt. Coglians–*Hohe Warte* (2,780 m a.s.l.) in the Carnic Alps and Mt. Triglav (2,864 m a.s.l.) in the Julian Alps are the two highest summits in the study area, respectively (Figure 1).

Sedimentary carbonate rocks prevail in the area, while igneous and metamorphic rocks are present to a limited extent in the Western Carnic Alps (Carulli, 2006) and Karavanke Mountains (Komac, 2005).

The 1981–2010 mean annual precipitation (MAP) is at its highest in the Julian Alps with totals higher than 3300 mm (Colucci & Guglielmin, 2015), but in the inner alpine Carnic sector decreases to 1600–1800 mm because of the precipitation shadow effect of the Prealps. Towards east the MAP decreases down to <1000 mm. The mean annual air temperature (MAAT) is strongly influenced by the altitudinal lapse rate but shows a decreasing trend from the prealpine reliefs to the inner alpine sectors and towards the east in Slovenia. The 1981–2010 MAAT point out to extremes of ca. −2.6°C on the highest peaks with the −2°C isotherm, which defines environments where frost action is dominant (French, 2007), estimated at 2,665 ± 90 m a.s.l. The 0°C-isotherm is estimated at an altitude of 2,370 ± 90 m a.s.l.

The present cryosphere in the study area consists of 23 ice bodies, covering a total area of 0.358 km^2 (Colucci, 2016) and more than a thousand caves located above 1,000 m a.s.l., which host snow, firn, and ice deposits (Colucci, Fontana, Forte, Potleca, & Guglielmin, 2016a). On the other hand, no active rock glaciers are present in the study area nowadays although few of them present uncertain activity due to their geomorphological characteristics. According to Colucci et al. (2016b) relict rock glaciers, distributed between 1,708 and 1,846 m a.s.l., cover an area of 3.45 km^2 and were likely active during the Lateglacial developing during different periods of the Holocene. The Little Ice Age (LIA) maximum extent of glaciers was estimated to 2.35 km^2 (Colucci, 2016) with a volume equal to 0.068 km^3 (Colucci & Žebre, 2016). At present (2012) the volume is reduced by 96% and equals 0.0027 km^3.

3. Materials and methods

The inventory of rock glaciers has been made by inspecting medium (0.5 m pixel; 1998, 2003, 2011 and 2014) and high resolution (0.15 m pixel; 2006–2009) aerial orthorectified photographs (orthophoto) (provided by Friuli Venezia Giulia Region and the Surveying and Mapping Authority of the Republic of Slovenia), as well as high resolution (1.0 m cell size) DTM and shaded relief interpolated from airborne laser scanning (LiDAR) data acquired between September 2006 and September 2009 for Friuli Venezia Giulia Region (RAFVG, 2006–2009) and between February 2011 and April 2015 for Slovenia (Ministry of the Environment and Spatial Planning, Slovenian Environment Agency, 2011–2015). The analysis of

Figure 1. Study area, highlighted with the red square, within the northern Mediterranean – Alpine region.

the aforementioned spatial data served as a basis for the field-based geomorphological mapping, accurate delineation of landforms and extraction of their morphometric characteristics (Figure 2).

3.1. Topographic base

The topographic base of the Main Map at a scale of 1:150,000 is composed of a 10 m resolution DTM (RAFVG, 2006–2009) and a 12.5 m resolution DTM (Surveying and Mapping Authority of the Republic of Slovenia, 2001–2005), portrayed with a background shaded relief map (*see Main Map*). The hydrography, comprising water courses of 1st, 2nd, 3rd and 4th order, the most important mountain peaks, the extent of glaciers and ice patches at the Little Ice Age peak and in 2012 (Colucci & Žebre, 2016) and the main towns are also shown. The coordinate system of the Main Map is WGS_1984_UTM_Zone_33N.

The topographic base of the 18 frames (from a to t; *see Main Map*), at a scale of 1:15,000, is a shaded relief map in grayscale covered by a colored DTM with a 1 m resolution. The coordinate system of the frames is the same of the Main Map (WGS_1984_UTM_Zone_33N).

The base layer of the geographical settings is a 30 m resolution ASTER Global Digital Elevation Model (ASTER GDEM) in a World Geodetic System 1984 (D_WGS_84) (http://gdem.ersdac.jspacesystems.or.jp/) with 20 m vertical and 30 m horizontal data accuracy (ASTER GDEM Readme File).

3.2. Data collection

Fieldwork, analysis of high resolution DTMs, orthophotos, Google Earth® and Bing® images were used in collecting the data for the map production. Fieldwork was carried out between 2013 and 2017 and included geomorphological mapping of periglacial features as well as verification of all landforms as recognized from remote sensing analysis, both for the Italian and Slovenian side of the southeastern Alps.

3.3. Geomorphological features

Periglacial landforms (rock glacier front, perimeter) were drawn on the basis of geomorphological mapping conducted in the field, and the analysis of LiDAR data, aerial photographs, and orthophotos.

By carefully looking at the surface morphology, consistent effort was used in the determination of the rooting zone where the rock glacier meets the input accumulation zone, and its upper limit. Rock glaciers were further classified according to the geometry into lobate rock glaciers that present a length/width ratio <1 and tongue-shaped rock glaciers, having typical length/width ratio >1 (Wahrhaftig & Cox, 1959).

3.4. Topographic names

The topographic names for the Italian side were derived from topographic maps Tabacco 1:25,000 (1993–2003) (sheets: 01, Sappada-S. Stefano-Forni Avoltri; 02, Forni di Sopra-Ampezzo-Sauris-Alta Val Tagliamento; 09, Alpi Carniche-Carnia centrale; 018, Alpi Carniche orientali-Canal del Ferro; 019, Alpi Giulie occidentali-Tarvisiano; 027, Canin-Val Resia-Parco Naturale Prealpi Giulie), by using toponyms generally derived from mountain peaks, huts or paths located in the vicinity of the landforms. The topographic names for the

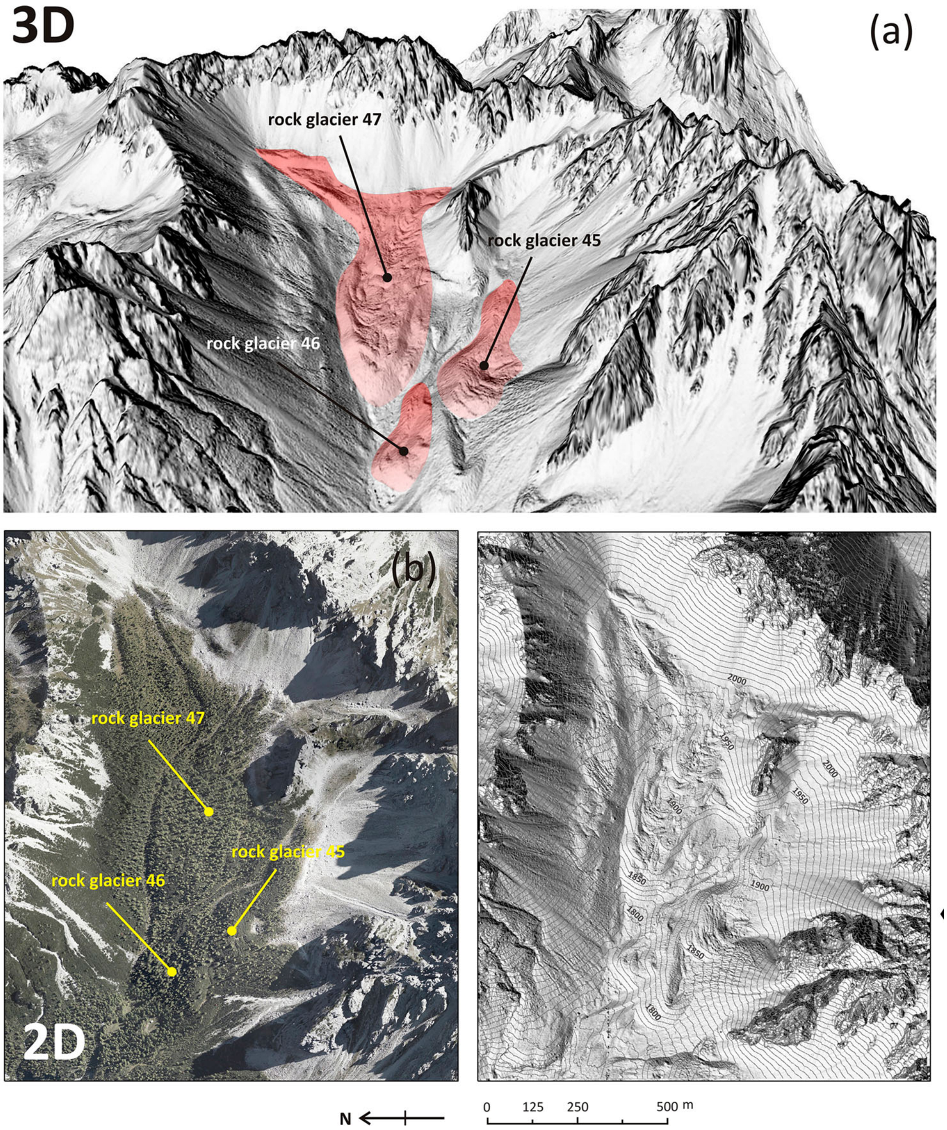

Figure 2. (a) The extent of Brica (n. 47 in the Main Map), del Cason (n. 45) and dell'Inferno (n. 46) rock glaciers as seen from the shaded relief projected on the 1 m cell size DTM in 3D view, (b) vegetation cover as seen from the ortophoto projected on the shaded relief in 2D view, and (c) their typical morphology resembling the lava flow shown on the shaded relief in 2D view.

Slovenian side were obtained from the Topographic maps of the Republic of Slovenia in scale 1:25,000 (1993–1999) (sheets: Koren 021; Kepa 022; Log pod Mangartom 039; Rateče 040; Kranjska Gora 041; Vrba 044; Spodnje Jezersko 046; Breginj 064; Soča 066; Ukanc 067;Kamniška Bistrica 073; Luče 074).

3.5. Volumetric ice content and water volume equivalent of rock glaciers

Ice volume of the studied rock glaciers was estimated on the basis of assumed volumetric ice content within intact rock glaciers and rock glaciers volume. Relict rock glaciers present heterogeneous aquifer and their present water storage is difficult to quantify without a detailed internal structure and dye-tracing measurements (Winkler et al., 2016). Our current data does not allow making any conclusion on their present capacity for storing the water. Worldwide field-supported studies, instead, suggest the volumetric ice content within active rock glaciers often range between 40% and 60% (e.g. Arenson, 2002; Hausmann et al., 2007, 2012), although the range can be even larger (e.g. Arenson et al., 2010) (Table 1). In this paper, the volumetric ice content of 40–60% has been considered as the most probable and thus used in ice volume estimations. Adopting the same percentage array as majority of the studies (e.g. Jones et al., 2018) also enables comparison among different research. Volume of rock glaciers was estimated by multiplying rock glacier surface area (A) and thickness (H). The first parameter was extracted from LiDAR data, using previously defined rock glacier polygon. The second parameter was estimated using an empirical rule established by Brenning (2005) based on field observations of rock glacier polygons. According to this power-law relationship (Equation (1)) the mean rock glacier thickness (H; in meters) is calculated as a function of surface area (A; in square kilometers) and two

Table 1. Field-based observations of ice content (%) by rock glacier volume reported in the literature.

Ice content (%) by volume	Study area	Methods	Reference
40–60	European Alps (Austria)	Geophysical investigation	Hausmann, Krainer, Bruckl, and Ullrich (2012)
45–60	European Alps (Austria)	Geophysical investigation	Hausmann et al., 2007
50–60	European Alps (Switzerland)	Borehole	Barsch (1977); Haeberli et al. (2006)
50–70	European Alps (Switzerland)	Borehole	Barsch et al., (1979); Haeberli et al. (2006)
40–70	European Alps (Switzerland)	Borehole	Arenson 2002)
55.7	Andes (Argentina)	Geophysical investigation	Croce and Milana (2002)
~65	Andes (Argentina)	Geophysical investigation, borehole	Arenson et al. (2010)
15–30	Andes (Chile)	Geophysical investigation, borehole	Monnier and Kinnard (2013)
35–40	European Alps (Italy)	Borehole	Krainer et al. (2015)

scaling parameters (c and β)

$$H = cA^{\beta} \tag{1}$$

where c is 50 and β is 0.2.

Ice volume estimates were subsequently used for calculating the water volume equivalent (w.v.e.) (Brenning, 2005; Jones et al., 2018) for the time when these rock glaciers were still active by assuming an ice density conversion factor of 900 kg m^{-3} (Paterson, 1994).

4. Results

52 rock glaciers have been mapped and analyzed in the southeastern Alps mainly concentrated in the Carnic Alps sector (27 rock glaciers) and in the Carnic Prealps (14 rock glaciers). The total area of rock glaciers in the southeastern Alps has been calculated to 3.40 km^2, which is 0.006% less than the previous estimations by Colucci et al. (2016b) (i.e. 1 rock glacier was excluded from results of this previous paper after field observations). Following the geomorphological approach described in Colucci et al. (2016b) and given the lack of geophysical investigations to determine the presence or lack of ice in the landforms, 47 rock glaciers have been classified as relict, and 6 of uncertain activity. The Tiarfin rock glacier (Figure 3) being the longest (ca. 1.1 km) among the studied landforms has been classified as complex in the group of the 5 of uncertain activity due to variable geomorphological

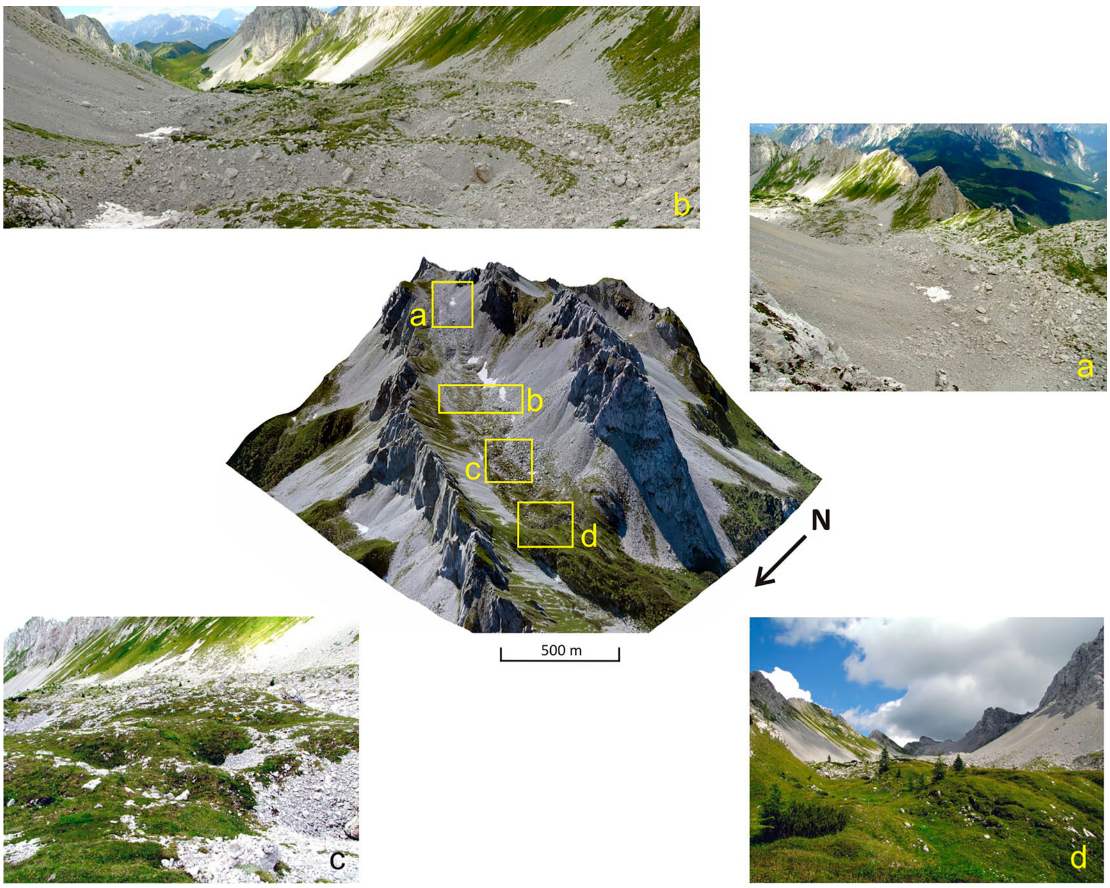

Figure 3. 3D image of Tiarfin rock glacier (n. 23 in the Main Map) realized by projecting the 2008 ortophoto on the 1 m cell size DTM. Details of different parts of this landform are highlighted in the Squares: (a) protalus ramparts located at the highest elevation of the rock glacier complex; (b) the central part where several ridges and furrows are clearly visible also from the field; (c) small dolines over the rock glacier surface likely due to thermokarst activity or suffosion; (d) the vegetated frontal part of the rock glacier with small Larix and Pinus mugo.

Table 2. Some statistics of the studied rock glaciers, including estimations of their paleo-ice volume and paleo-water volume equivalent.

Number	Name	Altitude [m a.s.l.]			Area	Length	Width	Mean thickness	Volume	Paleo RG's ice volume (40–60%)	Paleo RG's water volume equivalent (40-60%)	Activity degree	Geometry
		MAX	min	mean	[km^2]	[m]	[m]	[m]	[10^{-3} km^3]	[10^{-3} km^3]	[10^{-3} km^3]		
1	Rioda	1890	1816	1858	0.057677	174	331	28.3	1.63	0.81 ± 0.16	0.73 ± 0.29	relict	lobate
2	Oberkofel	1832	1745	1782	0.025767	152	131	24.1	0.62	0.31 ± 0.06	0.28 ± 0.11	relict	tongue shaped
3	Morganlaite	1732	1659	1699	0.103006	235	574	31.7	3.27	1.63 ± 0.33	1.47 ± 0.59	relict	lobate
4	Malins	1760	1729	1748	0.018998	119	155	22.6	0.43	0.21 ± 0.04	0.19 ± 0.08	relict	lobate
5	dell'Agriturismo	1800	1645	1718	0.208541	797	288	36.5	7.62	3.81 ± 0.76	3.43 ± 1.37	relict	tongue shaped
6	204–3c	1837	1674	1727	0.068599	656	129	29.3	2.01	1.00 ± 0.20	0.90 ± 0.36	relict	tongue shaped
7	Vinadia	1808	1736	1775	0.0550656	324	128	27.5	1.39	0.70 ± 0.14	0.63 ± 0.25	relict	tongue shaped
8	Ba	1791	1708	1752	0.042571	253	226	26.6	1.13	0.57 ± 0.11	0.51 ± 0.20	relict	tongue shaped
9	Esse	1814	1727	1774	0.019911	152	164	22.8	0.45	0.23 ± 0.05	0.20 ± 0.08	relict	lobate
10	Ta	1778	1724	1751	0.011384	132	100	20.4	0.23	0.12 ± 0.02	0.10 ± 0.04	relict	tongue shaped
11	S. Pietro	1748	1654	1688	0.052790	177	493	27.8	1.47	0.73 ± 0.15	0.66 ± 0.26	relict	lobate
12	Pieltinis	1793	1708	1755	0.091017	150	731	31	2.82	1.41 ± 0.28	1.27 ± 0.51	relict	lobate
13	Torondon	1809	1656	1730	0.055888	467	132	28.1	1.57	0.78 ± 0.16	0.71 ± 0.28	relict	tongue shaped
14	Crostis	1980	1920	1946	0.033688	241	147	25.4	0.85	0.43 ± 0.09	0.38 ± 0.15	relict	tongue shaped
15	Dimon	1742	1635	1698	0.054216	188	223	27.9	1.51	0.76 ± 0.15	0.68 ± 0.27	relict	lobate
16	dell'Amicizia	1857	1771	1816	0.145258	417	517	34	4.94	2.47 ± 0.49	2.22 ± 0.89	relict	lobate
17	Rosskofel	1751	1638	1697	0.045530	184	314	27	1.23	0.61 ± 0.12	0.55 ± 0.22	relict	lobate
18	Vršič 3	1199	1153	1177	0.010605	112	92	20.1	0.21	0.11 ± 0.02	0.10 ± 0.04	relict	tongue shaped
19	Vršič 1	1115	1004	1044	0.053522	267	214	27.8	1.49	0.75 ± 0.15	0.67 ± 0.27	relict	tongue shaped
20	Vršič 2	1104	996	1044	0.025222	289	100	24	0.6	0.30 ± 0.06	0.27 ± 0.11	relict	tongue shaped
21	di Razzo	2078	2038	2054	0.005410	49	94	17.6	0.1	0.05 ± 0.01	0.04 ± 0.02	relict	lobate
22	Tudaio	2041	1998	2024	0.012066	77	139	20.7	0.25	0.12 ± 0.02	0.11 ± 0.04	relict	lobate
23	Tiarfin	2275	2080	2148	0.142836	1092	135	33.9	4.84	2.42 ± 0.48	2.18 ± 0.87	uncertain	tongue shaped
24	Piova	1924	1859	1896	0.064682	228	245	28.9	1.87	0.94 ± 0.19	0.84 ± 0.34	relict	lobate
25	Tartoi	1923	1883	1896	0.007372	83	67	18.7	0.14	0.07 ± 0.01	0.06 ± 0.02	relict	tongue shaped
26	Casera Tragonia	2113	1897	2025	0.064910	558	130	28.9	1.88	0.94 ± 0.19	0.85 ± 0.34	relict	tongue shaped
27	CHIARAnda	2012	1842	1925	0.127010	367	322	33.1	4.2	2.10 ± 0.42	1.89 ± 0.76	relict	tongue shaped
28	Sella Nevea	1234	1107	1177	0.483944	505	1471	43.2	20.93	10.46 ± 2.09	9.42 ± 3.77	relict	lobate
29	7 Triglav lakes Valley 3	1823	1744	1789	0.070142	145	833	29.4	2.06	1.03 ± 0.21	0.93 ± 0.37	relict	lobate
30	7 Triglav lakes Valley 2	1777	1701	1743	0.057968	141	503	28.3	1.64	0.82 ± 0.16	0.74 ± 0.30	relict	lobate
31	7 Triglav lakes Valley 1	1776	1679	1711	0.077690	180	591	30	2.33	1.17 ± 0.23	1.05 ± 0.42	relict	lobate
32	Orlice 1	1886	1847	1872	0.010259	73	145	20	0.21	0.10 ± 0.02	0.09 ± 0.04	relict	lobate
33	Vrtača	1843	1808	1824	0.004042	56	121	16.6	0.07	0.03 ± 0.01	0.03 ± 0.01	relict	lobate
34	Skuta	2076	2020	2052	0.017214	91	178	22.2	0.38	0.19 ± 0.04	0.17 ± 0.07	relict	lobate
35	Veliki Zvoh	1688	1657	1669	0.009755	58	197	19.8	0.19	0.10 ± 0.02	0.09 ± 0.03	relict	lobate
36	dei Cadorini	1740.7	1565.9	1665.8	0.063103	436	148	28.8	1.82	0.91 ± 0.18	0.82 ± 0.33	relict	tongue shaped
37	di Giaf	1844	1639	1749	0.208567	269	845	36.5	7.62	3.81 ± 0.76	3.43 ± 1.37	uncertain	lobate
38	Urtisiel	1524	1370	1459	0.051371	309	172	27.6	1.42	0.71 ± 0.14	0.64 ± 0.26	relict	tongue shaped
39	367	1810	1710	1759	0.013245	127	105	21.1	0.28	0.14 ± 0.03	0.13 ± 0.05	relict	tongue shaped
40	di Lavinal	1954	1794	1881	0.077547	170	467	30	2.33	1.16 ± 0.23	1.05 ± 0.42	uncertain	lobate
41	Valbinon	1915	1784	1842	0.125230	356	370	33	4.13	2.07 ± 0.41	1.86 ± 0.74	uncertain	lobate
42	degli Sfiniti	1915	1842	1868	0.033291	218	154	25.3	0.84	0.42 ± 0.08	0.38 ± 0.15	relict	tongue shaped
43	di Canpuròs	1998	1917	1962	0.024438	219	128	23.8	0.58	0.29 ± 0.06	0.26 ± 0.10	uncertain	tongue shaped
44	della Cresta	1851	1728	1798	0.052554	365	164	27.7	1.46	0.73 ± 0.15	0.66 ± 0.26	uncertain	tongue shaped

(Continued)

Table 2. Continued.

Number	Name	Altitude			Area	Length	Width	Mean thickness	Volume	Paleo RG's ice volume (40–60%)	Paleo RG's water volume equivalent (40–60%)	Activity degree	Geometry
		[m a.s.l.]											
		MAX	min	mean	[km^2]	[m]	[m]	[m]	[10^{-3} km^3]	[10^{-3} km^3]	[10^{-3} km^3]		
45	del Cason	1813	1740	1778	0.022491	132	154	23.4	0.53	0.26 ± 0.05	0.24 ± 0.09	relict	lobate
46	dell'Inferno	1920	1812	1861	0.061749	235	188	28.6	1.77	0.88 ± 0.18	0.80 ± 0.32	relict	tongue shaped
47	di Brica	1991	1784	1896	0.145614	907	178	34	4.95	2.48 ± 0.50	2.23 ± 0.89	relict	tongue shaped
48	Cassiopea	1824	1784	1801	0.008959	173	72	19.5	0.17	0.09 ± 0.02	0.08 ± 0.03	relict	tongue shaped
49	di Suola	1976	1947	1963	0.013169	131	152	21	0.28	0.14 ± 0.03	0.12 ± 0.05	relict	lobate
50	Monte Pramaggiore	2084	1909	2021	0.069653	341	170	29.3	2.04	1.02 ± 0.20	0.92 ± 0.37	relict	tongue shaped
51	Casera Pramaggiore	1990	1829	1902	0.062867	416	191	28.8	1.81	0.90 ± 0.18	0.81 ± 0.33	relict	tongue shaped
52	Rua	1925	1813	1874	0.034908	236	128	25.6	0.89	0.45 ± 0.09	0.40 ± 0.16	relict	tongue shaped
	mean	1820.8	1719.7	1770.5	0.065363	273.635	272.038	26.9	2.11				
	total				3.398902				109.48				

characteristics along the longitudinal section, from its rooting zone to the terminus. It has the highest mean elevation (2,148 m a.s.l.) developing from 2,275 m a.s.l. to 2,080 m a.s.l. The upper part is characterized by a series of well-developed and sharp protalus ramparts located at the highest elevation of the rock glacier complex (Figure 3(a)). Here both the Alpine permafrost index map (APIM) (Boeckli, Brenning, Gruber, & Noetzli, 2012) and a Bottom Temperature of Snow cover (BTS) measurements campaign performed in March 2013 point to a likely presence of permafrost in the scree slope. The central part of the rock glacier is characterized by several ridges and furrows clearly recognizable also from the field (Figure 3(b)). Small dolines likely due to thermokarst activity or suffusion is a characteristic of the sector between roughly 2,120 and 2,080 m a.s.l. (Figure 3(c)) with increasing vegetation cover moving towards the frontal part of the rock glacier where small *Larix* and *Pinus mugo* grow over continuous meadows (Figure 3(d)).

The regional mean altitude of all the rock glacier's fronts is calculated to 1,720 m a.s.l. (st. dev. 230 m). Rock glaciers are generally characterized by discontinuous to continuous vegetation cover (Figure 2), mainly *P. mugo*, *Larix* and *Picea* with only nine of them occurring above the timber line as in the case of Tiarfin rock glacier (Figure 3).

The total volume of the studied rock glaciers has been estimated to 0.109 km^3 (Table 2). By applying the assumed ice content of 50 ± 10%, the total volumetric ice content of rock glaciers is 0.055 ± 0.011 km^3, while their w.v.e. is 0.049 ± 0.010 km^3 (Table 2). As a reference, this is roughly 50% less than the estimated water volume of lake Bohinj (Slovenia; See the Main Map) the largest permanent lake in the study area (0.0997 km^3; Hlad and Skoberne (2001)). The volume of the artificial lake of Sauris (see the Main Map) in the Carnic Alps is calculated to 0.07 km^3. Since the majority of rock glaciers were defined as relict, their volume estimates and therefore also the ice content and w.v.e. are given for their active state in the past. It has been inferred on the basis of the paleoclimate analysis that these rock glaciers are likely related to the Younger Dryas cold phase; however, older age for some of them cannot be excluded. Only 6 rock glaciers among the identified 52 are defined as of uncertain activity degree of which 1 as complex. These 6 rock glaciers may still contain some ice also in the recent climate, but most probably significantly less than during the Younger Dryas. It is worth noting that there are no direct field measurements of rock glacier thickness and ice content in our study area, therefore these are unknown variables and their uncertainty is difficult to quantify. The power-law relationship (Equation 1) for calculating the mean rock glacier thickness used in our study was developed for rock glaciers in Central Chile (Brenning, 2005), which means it cannot necessarily account best for our regional inventory. Apart from that, also the genesis (permafrost origin versus glacigenic origin) of the studied rock glaciers, strongly influencing the ice content estimations, is uncertain as well. All in all, our results present the first-order approximation and more field research is needed to better address and understand these uncertainties.

The estimated total volumetric ice content of rock glaciers in the southeastern Alps during Younger Dryas is similar to the ice volume of glaciers during Little Ice Age in the same area. The latter has been calculated to 0.068 km^3 (Colucci & Žebre, 2016).

5. Conclusions

A revised mapping of rock glaciers in several sectors of the southeastern European Alps (Carnic Alps and Prealps, Julian Alps and Prealps, southern Karavanke Mountains) has been produced for the first time after verification of all the landforms on the field. Detailed geomorphological mapping performed through LiDAR surveys allowed a revised quantification of area, thickness and volume of rock glaciers in order to estimate their paleo-ice volume for the time when such landforms were still active, by using a power-law equation. Moreover, a detailed morphology of every rock glacier of the Italian and Slovenian southeastern Alps is now clearly visible in the Main Map. The estimated total volumetric ice content of rock glaciers, which are thought to have been formed during the Younger Dryas cold event, is close to the ice volume of glaciers calculated in this area at the peak of the Little Ice Age.

Software

The maps were produced by means of Esri ArcGIS v. 10.4, while Adobe Illustrator CS6 and Adobe InDesign CS6 were used for graphic operations and layout building, respectively.

Author contribution

RRC conceived this study. CB realized the map, elaborated the RAW LiDAR data and undertook the GIS/statistical analysis. RRC, CB and MŽ made the field observations. RRC and MŽ wrote the manuscript and edited tables and figures, with the help of CB.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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